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An Algorithm for Leak Locating using Coupled Vibration of Pipe-Water

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Key Words : Leak Detection (누수탐지), Acoustic Emission(음향방출), Correlation Method(상관법), Acoustic Wave Propagation(음파전달), Water Pipeline(수도배관).

ABSTRACT

Leak noise is a good source to identify the exact location of a leak point of underground water pipelines. Water leak generates broadband noise from a leak location and can be propagated to both directions of water pipes. This sound propagation due to leak in water pipelines is not a non-dispersive wave any more because of the surrounding pipes and soil. However, the necessity of long-range detection of this leak location makes to identify low-frequency acoustic waves rather than high frequency ones. Acoustic wave propagation coupled with surrounding boundaries including cast iron pipes is theoretically analyzed and the wave velocity was confirmed with experiment. The leak locations were identified both by the acoustic emission (AE) method and the cross-correlation method. In a short-range distance, both the AE method and cross-correlation method are effective to detect leak position. However, the detection for a long-range distance required a lower frequency range accelerometers only because higher frequency waves were attenuated very quickly with the increase of propagation paths. Two algorithms for the cross-correlation function were suggested, and a long-range detection has been achieved at real underground water pipelines longer than 300m.

1. Introduction

Water pipelines network is an important component of the water supply facilities. Due to the water pipelines are buried under ground, it is difficult to identify the degree of deterioration of the underground water pipelines. This makes the maintenance of the pipelines not effective. In the case of South Korea, a recent government statistics report says that those pipelines aged more than 10 years are about 52% of the whole length 120,405 Km and about 14 % of the total produced water is leaked in a year.[1] This leak problem causes various social, environmental and economical costs.

Because the leak locating of the water pipelines underground is basically very difficult to identify by eye inspection, the detection technology based on leak noise is widely used, including listening rods, hydrophones, and ground microphones.[2]

An acoustical correlation analysis was suggested for a better leak detection in 1970s, but it was not that effective, which could detect in a very short distance.[3] In 1990s, Fuchs and Riehle [4] reported a precise leak detection result with a cross-correlation function after Fourier transform of measured signals. After this the leak noise correlator became to be used widely with commercial products.[5]

However, the leak noise correlator needs to know the exact sound speed inside water-filled pipelines and the time arrival difference to detect precise leak location. Pinnington and Briscoe [6] and Muggleton et al [7] in UK analyzed theoretically the vibration mode of water-filled pipelines due to leak and the sound propagation speed in water surrounded by pipelines and underground soil. Hunaidi and Chu [8] showed that the vibration related to acoustic propagation in water-filled pipes is dominant at low frequencies in their experimental research with a fluid-pipe coupled system of plastic pipelines, which has high damping property.

Acoustic emission (AE) technique with ultrasonic sensors is also used but it is known that the AE technique with correlation is effective especially at a short range detection.[9]

For a longer range distance, high sensitivity accelerometers are widely used to detect the vibrational motion, which is coupled with sound pressure propagation in water, due to leak in underground pipelines.[8] These sensors are effective because they could be attached on the surfaces of pipelines or stop valves etc. Apart from that, Pinnington and Briscoe [6] suggested a piezoelectric wire sensor to detect the pressure variation inside the water-filled pipelines.

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In this study, two types of sensors, AE sensors and accelerometers, are utilized to detect leak location of pipes. But in the case of AE sensor, a new approach using AE signal hit number method is applied rather than the cross-correlation method.

In the case of accelerometers, two algorithms are suggested to estimate the time delay with the cross-correlation method. First algorithm is a conventional FFT-based method and the other algorithm, which is a new suggestion, adopts an optimal window with FFT-based method for better precision.

For this study, a leak detection facility with 120 m long experimental pipelines have been constructed with various accessories and valves. Also real underground water supply pipelines of more than 300 m long were used for demonstrating developed algorithms for leak detection.

2. Leak noise and its propagation

When a leak at water pipelines under ground due to cracks, or holes occurs, it generates a leak signal with broadband.(7) This leak signal could be distinguished from temporal noises, because a leak is continuous.

The magnitude of a leak signal depends upon the pressure drop at the leak point, the shape and size of holes.(8) The leak noise propagates to the both longitudinal ends of a pipeline from the leak location. Thus the propagation of a leak signal is strongly coupled with water, pipeline structures and surrounding media.

It is known that "$s = 1$" wave, which is a fluid-borne axisymmetric wave (8), and "$n = 0$" mode, which is so called "breathing mode" vibration of a cylindrical shell (10), are important in detecting the leak location when accelerometers are used.

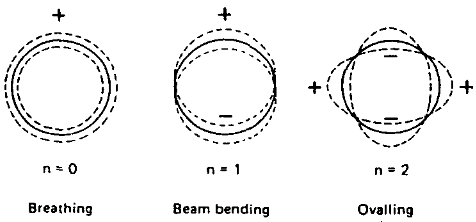


Fig. 1 Mode shapes of a cylindrical shell.(10)

The wave speed of "$s = 1$" wave due to leak of a underground pipeline is affected not only by pipe materials but also by surrounding media of the pipe, such as soil.

Considering the fact that the effect due to the surrounding media of the pipe is very small, the propagation speed of the leak signal ("$s = 1$" wave) can be expressed as (7)

$$c = c_f\left[1 + \frac{2B_f/d}{Eh/d^2 - \rho h\omega^2}\right]^{-1/2}, \qquad (1)$$

where $c_f = (B_f/\rho_f)^{1/2}$ is the wave speed in a free space, B_f is the bulk modulus of fluid, ρ_f is the fluid density and ω is frequency. E is Young's modulus, d is the diameter, h is the thickness, ρ is the material density of the pipe.

Equation (1) represents that the wave speed c due to leak has dispersive property, where the wave speed can be varied with frequency. But it must be noted that the "$s = 1$" wave will propagate only until the frequency reaches at "$n = 0$" mode frequency, which is known as "ring frequency" f_r as [10]

$$f_r = c_\ell'/\pi d, \qquad (2)$$

where $c_\ell' = [E/\rho(1-\nu^2)]^{1/2}$ is the speed of the quasi-longitudinal wave of the pipe and ν is Poisson's ratio.

Table 1 and Figure 2 show calculated wave propagation properties due to leak in underground 65A water-filled pipes with various materials of PVC, steel and cast iron.

Figure 2 clearly shows that the propagation speed of "$s = 1$" wave, which is related to leak noise, varies with frequency except the wave speed in free space of water (dashed line in Figure 2), which is constant over frequency and this is known as a non-dispersive wave.

Table 1 Wave propagation properties in various 65A pipes (d =72.7 mm, h =3.65 mm).

material	PVC	steel	cast iron
Young's Modulus E (N/m^2)	5.0×10^9	2.0×10^{11}	1.1×10^{11}
density ρ (kg/m^3)	2000	7800	7100
Poisson's ratio ν	0.4	0.28	0.26
quasi-longitudinal wave speed c_ℓ' (m/sec)	1725	5270	5434
ring frequency f_r (Hz)	7559	23111	23801
s=1 wave speed c (m/sec)	475	1356	1175

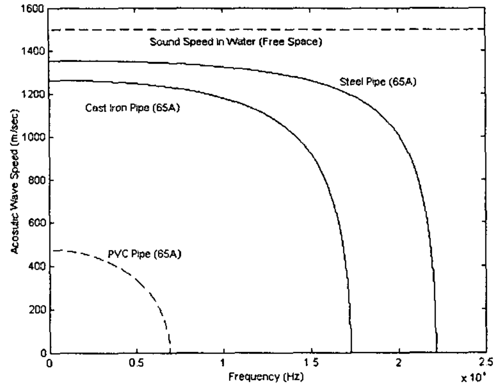


Fig. 2 Leak noise propagation speed against frequency in water filled pipes (65A size).

3. Detection Algorithms

As shown in Figure 3, a simple water pipeline with a leak and two sensors is considered. It is assumed that the leak location is positioned between the two sensors with the distances of d_1 and d_2. If d_1 and d_2 are different each other, then there must be an arrival time difference, or time delay $\tau_d = t_1 - t_2$, between the two sensors when there is a leak noise.

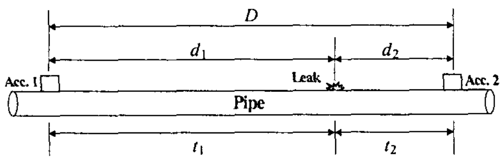


Fig. 3 Time arrival difference.

The distances of d_1 and d_2 in Figure 3 can be calculated when the leak noise propagates with the speed c as

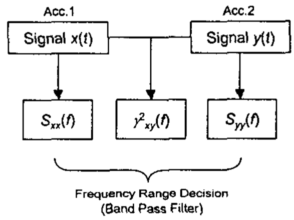
$$d_1 = (D + c\tau_d)/2 \qquad d_2 = (D - c\tau_d)/2, \tag{3}$$

where D is the distance between the two sensors. From equation (3), it is necessary to know the value of the time delay τ_d for the calculation of leak location.

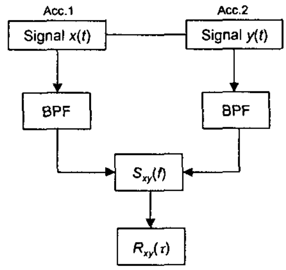
In this paper, two algorithms are suggested to estimate the time delay. *Algorithm 1* is a conventional FFT-based method and *algorithm 2*, which is a new suggestion, adopts an optimal window with FFT-based method for better precision. The details are as the followings.

Algorithm 1 for the estimation process of the time delay in the cross-correlation function of the measured signals can be summarized as can be seen from Figure 4(a) and (b). Since the auto-spectra $S_{xx}(f)$ and $S_{yy}(f)$, and coherence function $\gamma_{xy}^2(f)$ can be calculated from the measured two leak signals, $x(t)$ and $y(t)$, a reasonable frequency band to detect the leak noise can be determined when both a relatively large magnitude of the autospectrum and a high coherence are satisfied in the frequency range as shown in Figure 4(a).

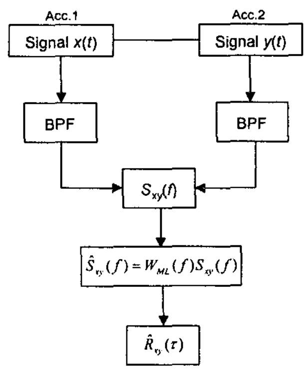
This indicates that the frequency band could be varied by the materials and sizes of pipelines. Thus band pass filters can be applied to measure the leak signals for the calculation of the cross-correlation function $R_{xy}(\tau)$, which offers time delay τ_d estimation as shown in Figure 4(b).



(a) Frequency band decision.



(b) Time delay estimation with algorithm 1.



(c) Time delay estimation with algorithm 2.

Fig. 4 Algorithms for leak location detection.

For algorithm 2, the optimal Maximum Likelihood window [11] can be considered to obtain the time delay between the two measured leak signals, $x(t)$ and $y(t)$. The Maximum Likelihood weighting function is expressed in the frequency domain in terms of the magnitude squared coherence function between $x(t)$ and $y(t)$, which can be written as

$$|\gamma_{xy}(f)|^2 = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)} \tag{4}$$

With this definition for magnitude squared coherence, the Maximum Likelihood weighting function can be shown to have the form [11]

$$W_{ML}(f) = \frac{|\gamma_{xy}(f)|^2}{|S_{xy}(f)|[1-|\gamma_{xy}(f)|^2]}, \tag{5}$$

where $|\gamma_{xy}(f)|^2 < 1$. It is known that the weighting function in equation (5) could provide a better peak detection of time delay estimation using cross-correlation, as shown in Figure 4(c). Thus the modified cross-spectrum $\hat{S}_{xy}(f)$ can be obtained as

$$\hat{S}_{xy}(f) = W_{ML}(f)S_{xy}(f) \tag{6}$$

and then the modified cross-correlation function $\hat{R}_{xy}(\tau)$ can be calculated by the inverse Fourier transform of $\hat{S}_{xy}(f)$.

4. Experiment by acoustic emission

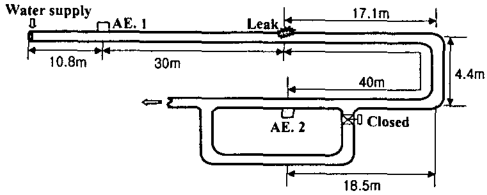
A systematic experiment at a leak test facility in KRISS (Korea Research Institute of Standards and Science) has been accomplished as shown in Figure 5. The total length of the steel pipeline is about 120 m and the size is 65A. The pressure inside the pipeline at test is about 3.6 kg$_f$/cm^2 before leak and drops to 3.2 kg$_f$/cm^2 during leak. Five ball valves, which are installed on the pipeline, were used as leak holes during leak detection experiment.

Two 60 kHz (PAC R6) resonant type acoustic emission (AE) sensors for detecting AE signals caused by water leak on the pipeline, a multi-channel Mistras 2001 (PAC) and a digital oscilloscope LeCroy 9354A are used for this AE experiment. The threshold level was set 43 - 77 dB by the leak signal strength and the wave speed of acoustic emission signal was set about 1250 m/sec.

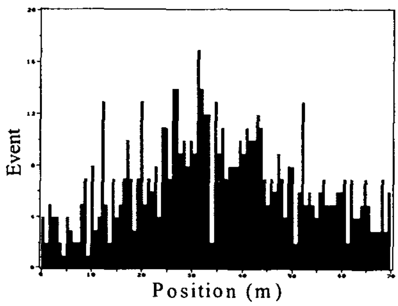
The leak location was decided by the number of AE hit as shown in Figure 5, in this case where the largest number of AE hit occurs at about 31m away from AE sensor No.1 when the actual location is 30 m away and the distance between the two AE sensors is 70 m.

After various cases of AE experiments, it is noted that the leak location error is increased when the distance between the two AE sensors, and this is because the AE signal is high frequency and decays very quickly with distance compared to low frequency signals.

Thus AE method for pipe leak detection is good at a relatively short distance case and when there is no high damping material in the propagation path of AE signals.



(a) AE sensors position and leak point.



(b) AE hit numbers against distance.

Fig. 5 Leak location by acoustic emission.

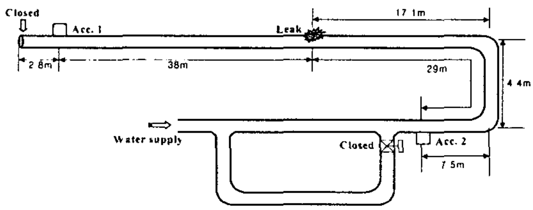
5. Experiment by cross-correlation

Leak location detection experiment with accelerometers at the same test facility as shown in Figure 4 was also accomplished according to the process in Figure 4(a) and (b), that is algorithm 1.

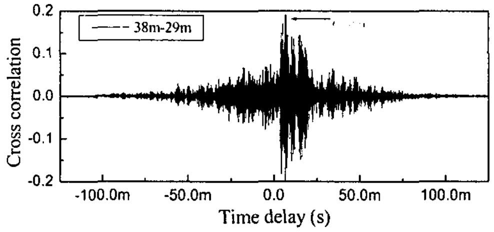
The distance D was 67 m, $d_1 = 38$ m and $d_2 = 29$ m, with two accelerometers (B&K 4370) and two filters (Krohn-Hite 3103) at the frequency band of 3 - 4 kHz. The signals from each accelerometer were transferred to signal conditioners (B&K Nexus) and then a signal analyzer (B&K Pulse).

After post-processing of the measured leak signals, cross-correlation functions were obtained through the process in Figure 4(a) and (b). The cross-correlation function obtained at this experiment plotted in Figure 7 shows the time delay of $\tau_d = 6.65$ msec, which represents $d_1 = 38$ m and $d_2 = 29$ m with the location error of 0.34 m (about 0.5 % of D).

This cross-correlation method with accelerometers shows better leak locating performance compared to that of the AE method at the same experimental facility shown in Figure 5.



(a) Accelerometers position and leak point.



(b) Cross-correlation function.

Fig. 6 Leak location by cross-correlation function with accelerometers.

Apart from the experiment at the test facility in KRISS in Figure 5, a series of leak detection experiment with accelerometers was also done at real underground pipelines in the city of Daejeon, South Korea as shown in Figure 7.

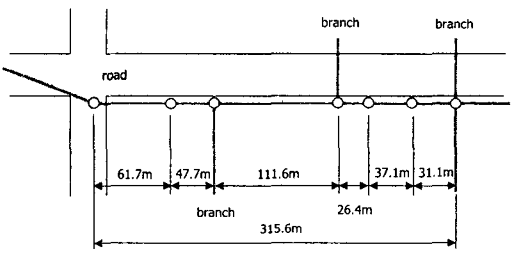


Fig. 7 Leak detection experiment for real underground pipelines.

The 100A sized cast iron pipelines buried about 1.5 m beneath the ground surface have seven manholes to access, and test cases were arranged to be D becomes about 150 m - 315 m. The leak was controlled by a ball valve, which was installed on the pipeline for the experiment. The accelerometers used in the tests were B&K 8313C and frequency band was set to 0 - 800 Hz. The other experimental set-up and post-processing (Algorithm 1) for the cross-correlation function was the same as the experiment in Figure 7.

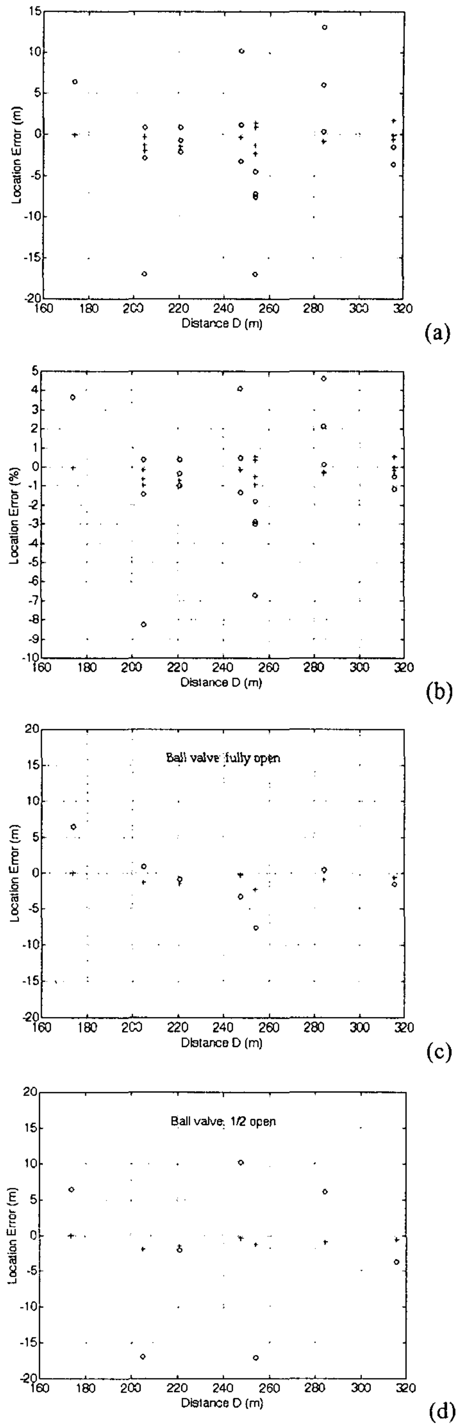


Fig. 8 Comparison of the two algorithms. O: Algorithm 1. +: Algorithm 2. (a) D against location error (m) (b) D vs location error (% of D) (c) D vs location error (fully open) (d) D vs location error (1/2 open)

Especially in this experiment, Algorithm 2 using optimal Maximum Likelihood windows shown in Figure 4(c) is also applied to compare with Algorithm 1. The wave speed of leak signal is assumed as 1375 m/sec for this experiment after initial measurement.

Figure 8(a) and (b) show that Algorithm 1 (○ marked) had a maximum about 20 m and 8 % of D locating error, but Algorithm 2 (+ marked) had less than 3 m and 1 % of D. The dashed lines in Figure 8(b) indicate ± 1 % of D error limits. Also the detection performance of the two algorithms were compared with the leak rate variation.

The leak rate was controlled by the opening angle of the leak control ball valve installed on the pipelines. As shown in Figure 8(c) and 8(d), Algorithm 1 gave maximum about 7.5 m and 17.0 m locating errors when the valve is fully open and 1/2 open respectively, however Algorithm 2 gave maximum about 2.5 m and 2.0 m locating errors when the valve is fully open and 1/2 open respectively.

In this leak rate variation test, Algorithm 2 showed stable leak locating performance without any notable performance changes at various conditions. From this experiment with the two algorithms, the performance of Algorithm 2, which showed the detection precision of less than 1 % of D, is much better than Algorithm 1.

6. Conclusions

This paper discusses the theoretical and experimental study on the detection of leak location of underground pipelines. Theoretical study describes propagation of leak signal and the background of leak detection theory with the cross-correlation function using accelerometers. A new algorithm for the cross-correlation function is suggested, which can be compared with a conventional one. The new algorithm showed very precise locating of leak position in real underground water pipelines.

Acknowledgement

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